Propulsion
De-Scope Options

FAME Technical Interchange Meeting (TIM)

August 15-16, 2001

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Introduction

A Variety of De-Scope Options Are Being Investigated in an Effort to Reduce the Total FAME System Cost in Order to Reduce the Possibility of Program Cancellation. Propulsion Stages Are Quite Expensive and Potentially Offer Significant Cost Savings

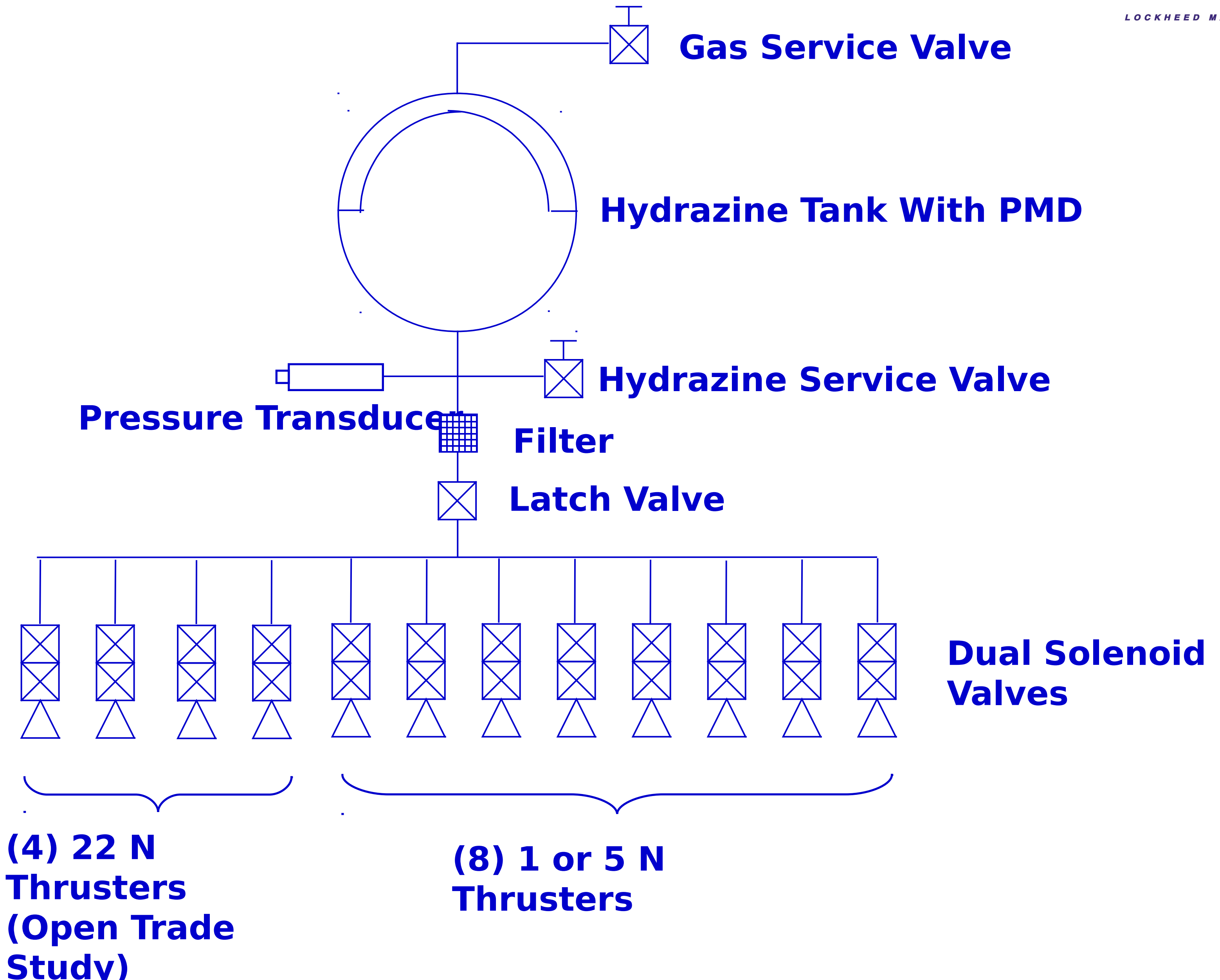
Trade Space

Options	Description	LV	Upper Stage	Propulsion System	Transfer Time (days)	Total Cost	Cost Savings	Mass Savings (lb)	Comments	Option Status
-1	Previous Design	60.2	1.8	4.3	1	66.3	0	0		Closed
0	Current Re-Designed 'Baseline'	60.2	0.8	3.7	1	64.7	1.6	50	Use Existing Tiros STAR 37XFP and Qualified 31 inch tank	Open
1	Delta 2420 LEO to GEO Transfer with All Electric Propulsion (EP)	51	0	10	1350	61	5.3	3500	Power Limited. Reaction Wheel or Thruster Gimbal required. Cost Savings does not justify the transfer time	Closed
2	Delta 2426 Sub Synch With Solid and EP	53.8	1.5	7.7	200-400	63	3.3	700-1300	Power Limited. Reaction Wheel or Thruster Gimbal required. Cost Savings does not justify the transfer time and system complexity	Closed
3	Delta 2425 Super Synchronous Transfer With Solid and EP	53.8	1.5	7.7	200-400	63	3.3	700-1300	Power Limited. Reaction Wheel or Thruster Gimbal required. Cost Savings does not justify the transfer time and system complexity	Closed
4	Delta 2425 Super Synchronous Transfer With Hydrazine and EP	53.8	0	7.7	300-400	61.5	4.8	1000	Power Limited. Reaction Wheel or Thruster Gimbal required. Cost Savings does not justify the transfer time and system complexity	Closed
5	Delta 2420 With Bi-prop Dual Mode Upper Stage	51	0	6	1	57	9.3	50 - 500	Packaging is more Challenging. Different Tank Volumes for fuel and oxidizer	Open
6	Delta 2420 With Bi-prop MMH/NTO Upper Stage and Monopropellant Hydrazine ACS	51	0	7	1	58	8.3	0-400	Bi-prop Tanks are of Equal Volume. Monopropellant Hydrazine for ACS in separate tank.	Open
7	Delta 2420 With Bi-Prop Separable Bi-prop stage with Permanent Hydrazine ACS	51	0	8	1	59	7.3	0-150	Bi-prop stage must be placed in a Disposal Orbit	Open
8	Delta 2425 Highly Eccentric Orbit (HEO), 400 Mile Perigee, Near Lunar Apogee	53.8	0	2	1	55.8	10.5	0	10-15 day Orbit Period dependent on Apogee Altitude. Causes significant change to th mission science collection orbit. Effects of the moon and earth must be accounted for	Open

Option -1: Propulsion Mission Requirements

- Provide Thrust for Spacecraft Orbit Raising, Attitude Control, and Stationkeeping
- Provide Single Fault Tolerant Design
  - Thruster Failure
  - Valve Leakage
- 5 Year Mission Life
  - Design For Delivery by August 15, 2003
    - Derived From Integrated Master Schedule
  - Design, Qualify, and Test for FAME Mission and Launch Environments
    - NCST-TP-FM001, FAME Test Plan
    - New or Re-Designed Systems Will Have Protoflight Testing
- Meet Launch Base Safety Requirements and Verification Process
  - EWR-127-1 TBD Version, Tailored for FAME
- Support Science Mission Requirements
  - Minimize CG Migration, Plume Contamination, and Minimum Impulse Bit
- Minimize Cost and Schedule Risk
  - Provide Most Flexible Design With Given Schedule and Budget

Option -1: FAME Propulsion Schematic



Option -1: Mission Sequence

- Launch Delta 2925 into FAME Super- Synchronous Transfer Orbit
  - 185 by GEO Alt + 320 Km
  - Apogee Selected for AKM Disposal Orbit
  - 10.6 Hour Period
  - Activate S/C and Wait 2.5 Days for Phasing and Orbit Determination
    - S/C Pointing, Slew Maneuvers, Spin- up, Spin Axis Precession, Nutation Control
- Fire On-Board STAR 37XFP Solid Rocket Motor to Circularize into a Circular Super-Synchronous Orbit
  - 1 Minute SRM Burn
  - Orbit Nominally Circular at GEO + 320 km
  - Dispose of the STAR 37XFP Transfer Stage
  - Orbit Drifts for Approximately 1 Month to Mission Longitude
    - Deploy Sunshield
    - Perform Payload Check Out
- Correct Launch Vehicle Errors and Transfer to the Mission Orbit With On-board Hydrazine System
  - 3 Axis Inertial Pointing With ACS Limit Cycle Motion

Option 0: Current Baseline

- 8 Thrusters Rather Than 12
  - Previous Design Had 4 Thrusters Hidden Behind Sun Shield Before Deployment
  - Smaller Thruster Forces Required With Smaller Overall Vehicle
    - Two 22N Thrusters
    - Six 1N Thrusters
  - Cost Savings $120K
- Accept Off-the-Shelf Tank Design
  - Options are Not Optimal - Too Big, Too Small, or Elastomeric Diaphragm
  - Previous Metal Diaphragm Qualification Program Cost $430K
- Use Existing Apogee Kick Motor (AKM) Case (STAR 37XFP)
  - Originally Built for TIROS-N for NASA/NOAA
  - Carried As a Spare After Propellant Quality Control Problem
    - Motor Currently Offloaded of Propellant
  - Case Has Been In Storage Since the Middle 1980’s
- Use Existing AKM Shipping and Handling Equipment
  - Previously Purchased For CLENMENTINE

Options 1-4: Electric Propulsion

- Electric Propulsion Delivers Greater Payload Fractions to Final Orbit
- Increased Propellant Utilization Efficiency (Specific Impulse)
  - Xenon Hall Thrusters Provide Best System Performance
    - Also Considered Xenon Ion and Arcjet Systems
- Reduction in Propellant Requirements to the GEO Orbit
- Smaller Delta 2400 Series Launch Vehicle Could be Used
  - Significant Cost Savings
- All Options Were Severely Power Limited
  - Additional Cost Complexity of Augmenting Solar Arrays Eliminates Potential Cost Savings
- Corresponding Reduction in Thrust Results in Large Trip Time
  - The Minimum Trip Time Was 7 Months Due to Limited Power
- Option Requires Thruster Gimbal or Reaction Wheel Control

Options 5-7: Liquid Upper Stages

- Options Use the Delta 2420 with No Upper Stage
- Replace the Launch Vehicle 3rd Stage (STAR 48)
- Replace the On-Board Apogee Kick Motor (AKM) (STAR 37XFP)
- Replaces or Augments the On-board Monopropellant Hydrazine System
- Mass Penalty Due to a Reverse Staging Effect
- Packaging Big Multiple Tanks is Challenging
- Requires High Performance Development Tankage
- All Stages Required Additional Helium Pressurization Systems
- Option is Promising for the 8 Foot Payload Fairing
  - Slim Margins for 9.5 and 10 Foot Payload Fairings
  - Requires Deployable Sun Shield (Not Currently in Cost or Mass Estimates)

Option 5: Dual Mode Bi-Propellant Upper Stage

- Uses Hydrazine (N_2H_4) for Both Bi-Propellant Fuel and for Attitude Control Thrusters
  - Nitrogen Tetroxide (NTO) N_2O_4 Oxidizer
- Reduced Tank Tank Quantity and Mass
- System Cannot Be Separated Before the Science Mission
  - NASA Disposal Orbit Requires Chemical System for the End of the Mission
- 6% Margin on the Current Payload Design in the 10 Foot Fairing
  - M. Johnson Desire is 25%
- ~40% Margin on the Current Payload in the 8 Fairing
  - Looks Good if We Can Fit
- More Analysis Required
  - Detailed Performance
  - System Packaging
  - Other Sub-System Review
  - Detailed Cost

Option 6: Conventional Bi-Propellant Upper Stage with Hydrazine ACS

- Hypergolic Bi-Propellant
  - Fuel: Monomethyl Hydrazine (MMH)
  - Nitrogen Tetroxide (NTO) N2O4 Oxidizer
- Blowdown Monopropellant Hydrazine System Similar to Current Baseline for ACS
- Payload Limited By Bi-Prop Thruster Performance, and additional Hydrazine Tank Weight
- 2% Mass Margin on Delta 2420-10
  - Insufficient Margin (M. Johnson PDR Desires 25%)
- ~30 % Payload Margin on Delta 2420-8 (8 Ft Fairing)
- More Analysis Required
  - Detailed Performance
  - System Packaging
  - Other Sub-System Review
  - Detailed Cost

Option 7: Separable Conventional Bi-Propellant Upper Stage

- Jettisons the Bi-Prop System Before Performing the Science Mission
  - Significant Reduces Sun Shading Effects
  - Improves the Vehicle Inertia Ratio for S
- Uses the Hydrazine ACS System for Debris Mitigation Disposal at End of the Mission
- Requires Additional Separation Interface and Control
  - More Complex Interface Due to Separable Command Interface the Bi-Prop Stage Equipment
- Additional Mass of Separation System Cut Into Already Thin Mass Margin on the Launch Vehicle
- Negative Mass Margin on Delta 2420-10
- ~15 % Payload Margin on Delta 2420-8 (8 Ft Fairing)
  - Cannot Get 25% Margin (M. Johnson PDR Desire)

Option 8: Highly Elliptic Orbit (HEO) Mission

- Investigates Elliptical Orbits With Apogees Up to 10 Times GEO Altitude
  - Uses Delta 2425 Launch Vehicle With STAR 48 3rd Stage
  - Nominal 650 km (400 Miles) Perigee
  - Orbit Period is 7 to 14 Days Depending on Apogee
  - Orbit is Insensitive to Launch Vehicle Error
    - No Correction Required
- Exceeding Lunar Altitude Degrades Orbit Due to Reverse Lunar Gravity Assist
  - Decreases Perigee Altitude
- HEO Mission Has No Delta Velocity Requirement
  - Mission Safe Hold and Science Collection Spin Must Be Handled by a Different System
    - PPT or Cold Gas System
- Requires Multiple Ground Stations With Gimbaled Antennae
- Communications RF System Requires Modification
  - High Gain Antennae
  - Store and Forward
- 150-250 Passes Through the Earth Radiation Belts
- ADCS: Lunar Gravity Effects, Solar Wind, Limited
- Science Impacts

Mission Analysis Methodology

- Define Disposal Orbits for Debris Mitigation
  - Determine AKM Transfer Stage and Final FAME Disposal Orbits
    - Based on NASA Guidelines
- Evaluate Launch Vehicle Performance to FAME Insertion Orbit
  - Penalize Delta 2425 for Performance to Higher FAME GTO Orbit
    - Mass Penalty is About 10 kg
- Perform AKM Sizing
  - Performance, Loads, Propellant Requirements Including Offload, Determine Mass Allocations and Staging Efficiencies
- Perform Stage Error Analysis
  - Pointing and Total Impulse Error Evaluation and Correction
- Evaluate Orbit Design
  - Calculate Delta Velocity Requirements For Maneuvers
  - Investigate Sub-Synchronous Transfer Option
- Calculate On-Board Hydrazine Requirements
  - Size the Hydrazine Tank

Propulsion Analysis

- Solid
  - Staging Performance for the Delta and STAR 37XFP
  - System Sizing and Motor Selection
  - Calculate Propellant Offloads and Offload Capabilities
  - Perform Total Impulse and Pointing Error Analysis
- Mass Properties Investigated at the Component Level
  - Provided Solid and Liquid System Mass Input Into Mechanical Mass Properties
- Liquid Hydrazine System Fuel Sizing
  - Blowdown Pressurization Pressurization Budget
- Thruster Performance
  - Thrust, Isp, Minimum Impulse
  - Inputs Supplied to Orbit and ACS Analyst
- Final Tank Sizing
  - Hardware Selection and Availability
  - Mechanical and Geometric Constraints

Propellant Budget

Event	Event Description	Delta V (m/s)	Ave Isp (sec)	Initial Pressure (psia)	Ave Thrust (N)	Initial Mass (kg)	Delta V Prop (kg)	ACS Prop (kg)	Prop Remaining (kg)	Burn Time (sec)
0									64.4	
1	Null Delta 3rd Stage Tip Off		160	350.0	5.23	1727.8		0.17	64.2	50
2	Inertial Pointing (3-axis limit cycle)		160	349.5	5.23	1727.6		0.05	64.2	16
3	Slew Manuevers		160	349.3	5.22	1727.6		0.22	64.0	67
4	Safe Hold Mode Spin up/down		160	348.6	10.43	1727.3		0.07	63.9	11
5	Spin-up FAME with SRM		220	348.4	10.35	1727.3		1.55	62.3	323
6	Active Nutation Control		160	343.7	4.96	1725.7		8.80	53.5	2783
7	Spin Axis Precession (6 degrees)		160	319.2	4.77	1716.9		0.35	53.2	116
8	STAR 37XFP Firing		290	318.3	38030	1716.6			53.2	53
9	Active Nutation Control		160	318.3	4.73	1010.6		1.73	51.5	572
10	Despin FAME with Spent STAR 37XFP		220	314.0	9.35	1008.8		1.25	50.2	289
11	Slew Manuevers		160	310.9	4.61	1007.6		2.48	47.7	845
12	Inertial Pointing (3-axis limit cycle)		160	304.9	4.55	1005.1		0.43	47.3	148
13	Hydrazine to Make-up Star 48 TI Error (.5%)		220	303.9	100.31	1004.7	13.44	0.36	33.5	8
14	Hydrazine to Make-up Star 48 Pointing Alt Error		220	274.7	95.10	990.9	0.42	0.01	33.1	0
15	Hydrazine to Make-up Star 37XFP TI Error (.5%)		220	273.9	93.86	990.4	3.32	0.09	29.6	2
16	Hydrazine to Make-up Star 37XFP Pointing Error		220	267.5	92.75	987.0	0.05	0.00	29.6	0.0
17	Jetison STAR 37XFP and Adaptor	0.5	220	267.4	92.65	987.0	0.23	0.01	29.4	0.1
18	Slew Manuevers		160	267.0	3.99	872.8		0.03	29.3	13
19	Inertial Pointing (3-axis limit cycle)		160	267.0	3.99	872.7		0.10	29.2	41
20	Decrease Perigee to Final GEO Orbit	5.44	220	266.8	91.77	872.6	2.20	0.15	26.9	4
21	Decrease Apogee to Final GEO Orbit	5.44	220	262.6	90.35	870.3	2.20	0.15	24.5	4
22	Slew Manuevers		160	258.6	3.86	867.9		0.30	24.2	120
23	Inertial Pointing (3-axis limit cycle)		160	258.1	3.84	867.6		1.36	22.9	555
24	Safe Hold Mode spin up/down		160	255.8	7.63	866.3		0.77	22.1	159
25	Raise Apogee to Disposal Orbit	5.44	220	254.5	87.59	865.5	2.18	0.15	19.8	4
26	Raise perigee to Disposal Orbit	5.44	220	250.7	86.30	863.2	2.17	0.15	17.4	4
28	5% Unusable Residual		160	247.1	7.32	860.8	3.22		14.2	690
29	Fuel Margin		160	242.2	80.97	857.6	12.55		1.7	243

64.4 Kg (142 lb) Propellant Load

Tank Selection (1 of 2)

- Tank Selection Issues Requires Additional Analysis
  - Requires Quantification of Propellant and Pressurization
  - Single Blowdown Tank vs. Augmented Pressurization Tank
- Tank Geometry
  - Oblate Spheroid Desired but Has Limited Availability
    - Reduces Spacecraft Overall Height Allowing Preferred Sun Angle Between the Sun Shield and Payload
  - Mounting Options Include Boss and Girth (Tabs or Skirt)
- PMD Selection Limits Availability
  - Passive PMD Is Not Possible (Accelerations, Spin, and CG Control)
  - Trade Elastomeric Tank Bladder vs. Metal Diaphragm
    - Metal Diaphragm Has Higher ΔP From Gas to Liquid
    - Metal Diaphragm Has Better Cg Control During Accelerations
    - Metal Diaphragm Is Single Use Only
    - Metal Diaphragm Eliminates Gross Mass Motion Slosh

Tank Selection (1 of 2)

- Cost and Delivery Schedule
  - Heritage Design Is Desirable
  - New Design and Qualification Possible (Lengthy Delivery and Costly)
  - New Tank Design and Qualification Requires 24 Months ARO
    - Program Schedule Supports New Tank Procurement
    - Multiple Designs and Vendors Available
      - PSI, Atlantic Research, Arde, Keystone
- Implication of Oversizing the Hydrazine Tank
  - Lowers the System Blowdown Ratio
    - Smaller BOL to EOL Thrust Variation
      - Effects on Nutation Control (Requires High Thrust)
      - Effects on Minimum Impulse (Requires Low Thrust)
    - Can Overfill to Correct Blowdown Ratio
      - Mass Penalty for Unused Propellant
  - An Oversized Tank is an Excellent Reservoir for Mass Margin
    - Allows for Contingency Operations, Science Mission ACS, or Extended Mission

Elastomeric Diaphragm Tank: PSI P/N 80388

- Maximum Expected Operating Pressure (MEOP) 350 psia
- Proof Pressure 527 psia, Minimum Burst 700 psia
- Qualified Propellant Load of 72.56 kg (160 lb)
- Geometry
  - 57.15 cm (22.5 in) Outside Diameter
  - Spherical with Offset Polar Outlet Tube
  - Volume 91.1 Liters (5555 cu in)
  - Tank Weight 7.03 kg (15.5 lb)
  - Four Girth Mounted Tabs With Slots
  - AF-E-332 Elastomeric Bladder

- Designed and Previously Flown for KoreaSat, CENTAUR, TOMS-EP, ROCSAT, KOMPSAT, INMARSAT 3, GGS
- Full Mil-Std-1522 Design, Analysis, and Qualification Testing
  - One Known Safety Waiver Required for Last Girth Weld Stress Relief

Big Metal Diaphragm Tank

- Atlantic Research Corporation (ARC) P/N AO882300
  - 31 inch Near Sphere (16,615 Cubic In)
- Maximum Expected Operating Pressure (MEOP) 318 psia
- Proof 472.5 psia, Minimum Burst 567 psia

  Polar Inlet and Outlet Tubes
  - Tank Weight 27.2 kg (60 lb)
  - Polar Boss Mounted with Threaded Receiver
  - AL 2219 Shell, AL 1100 Metal Diaphragm
- Currently Under Development for Boeing
- Large Size Accommodates Blowdown Pressurization
- Large Tank is Difficult to Package in the Current Design

Small Metal Diaphragm Tank

- Atlantic Research Corporation (ARC) P/N AO882300
  - 19 x 21 Inch Elongated Sphere (3125 Cubic In)
- Maximum Expected Operating Pressure (MEOP) 300 psia
- Proof 450 psia, Minimum Burst 650 psia

  Polar Inlet and Outlet Tubes
  - Tank Weight 7.62 kg (16.8 lb)
  - Polar Boss Mounted
  - AL 2219 Shell, AL 1100 Metal Diaphragm
- Developed for NRL CLEMENTINE Program
- Requires Secondary Pressurization System
  - Fill tank to 97% with Hydrazine
  - 110 lb Hydrazine Maximum Capacity
  - Use Would Limit Payload Size and/or Inertia

Pulsed Plasma Thruster (PPT)

- PPT is Under Investigation for Active Attitude Control During Science Collection
  - Detailed Requirements Analysis Being Performed by Tae Lim of ADCS
- Modern Design Currently Flying on EO-1 Satellite
  - New Developments With TIP/NOVA Design heritage 1970’s and 1980’s
- Teflon Bar Propellant
- Two Opposing Nozzle Configuration
- 5 Throttle Ranges (Impulse Bit/ Pulse)
- TBD Cost >$1M For the Minimum Three Thruster System
- Mass 4.95 Kg
- Input Power 70W, 28V, 1 Pulse/Sec
- Pulse Frequency up to 1 Hz
- Specific Impulse 650-1400 Seconds
- Impulse Bit 90-860 micro-N-seconds
- Upgrades Required for Use on FAME
  - Fuel Capacity, PMP, Electronics Switching, Program Documentation
  - Qualification Upgrade May be Required

Propellant Slosh

- Fuel Sloshing in the Propellant Tank Has Not Been Analyzed
- Gross Mass Sloshing is Well Understood
  - CG Control During Expulsion and Accelerations
    - Controlled With Tank Specifications
    - Verified With Qualification or Acceptance Testing
      - Non-Destructive Testing is Possible With Elastomeric Diaphragm Tank but Not Metallic Diaphragm
- Fine Motion of Propellant and Damping Characteristic is Not Well Understood
  - Interaction Between Excitation Sources and Damping Propellant Motion
    - Evaluate All Excitation Sources: Thrusters, Motors, Torque Rods, Thermal Variations, Eclipse Effects
    - Model Propellant Viscous Motion and Damping Effects
  - Mathematical Models Will Take Several Months to Generate
  - Model Verification Through Testing is Not Possible
  - 1g Environment Swamps Subtle Slosh Effects

Tank Procurement

- Detailed Discussion With Potential Vendors Ongoing
  - PSI, Arde, Atlantic Research, Keystone
- Baseline Tanks Are Off-the-Shelf With 8-16 Month Delivery
- Procurement Package Must Be Updated
- Auxiliary Pressurization Tanks Are Still Under Investigation
    - 14 Month Lead Time Delivery Requires a PDR Decision
  - Multiple Vendors Possible
    - Kaiser Compositek
    - Lincoln Composites
    - Structural Composites Industries (SCI)
- Component Specification Under Development

Hydrazine Thruster Procurement

- Thruster Quantity and Force Selection
  - Final Requirement Definition
    - Spin Control and 3-Axis ACS
    - SAP, ANC, and Vehicle Delta V Thrusters
    - Minimum Impulse Bit and Maximum Thrust Are Design Drivers
    - Conflicting Requirements for a Single Thruster Size
- Multiple Designs and Vendors
- 8-12 Month Delivery
- Detailed Discussion With Potential Vendors Ongoing
- General Dynamics, Atlantic Research, ValveTech Consortium
- Component Specification Under Development
- Procurement Package Must Be Updated

Propulsion Issues

- Narrowing Options for PDR Preparation
  - Liquid Upper Stage Options Require Significantly More Effort
- Tight Schedule to Meet the Bus Integration Requirements
  - Expedited Procurement Process Required If Procurement is Delayed
- Major Procurements Are Well Before CDR
  - Analysis Accuracy Due to Vehicle and Mission Design Uncertainty
- Tank Selection (PMD Design)
  - Undefined Tank Slosh Requirements
- Minimize Different Thruster Designs for Cost Efficiency (Specifications, Procurements, Integration, and Test Simplification)
- Thruster Solar Precession Back-Up Requirement
  - Small Impulse Bit Control System Would Be Required
  - Requirement Evaluation and Definition Are Necessary
    - Long Lead Items Are Required, 18 Months for the Tank
      - TBD Months for Pulsed Plasma Thruster
- Mission,Thruster, and Tank Analysis Are Still Under Investigation